



Jet Propulsion Laboratory
California Institute of Technology

**AFTA SCIENCE DEFINITION TEAM MEETING,
National Harbor, MD**

Coronagraph Architecture Downselect Results

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NASA Goddard Space Flight Center

January 9, 2014



Purpose and Approach

- **Objective:** Recommend a primary and backup coronagraph architecture to focus design and technology development to **maximize readiness for new mission start in FY17**
- Recommendation by ExEPO and ASO based on inputs from
 - **AFTA SDT:** Sets the science requirements
 - **ACWG:** Delivers technical FOMs and technology plans
 - > *Aim for the positive: a consensus product*
 - > SDT delivers science FOMs
 - **TAC:** Analysis of technical FOM, TRL readiness plans, and risks
- **ExEPO and ASO** recommendation to **APD Director** based on:
 - Technical and Programmatic criteria
 - Musts (Requirements), Wants (Goals), and Risks
 - Opportunities
- **APD Director** will make the decision

ACWG = AFTA Coronagraph Working Group: representatives of ExEPO, ASO, SDT, Community

Acronyms:

ExEPO: Exoplanet Expl. Prog. Office
ASO: AFTA Study Office
SDT: Science Definition Team
FOM: Figure of Merit
TRL: Technology Readiness Level

TAC: Technical Analysis Committee

Alan Boss (Carnegie Inst.)
Joe Pitman (EXSCI)
Steve Ridgway (NOAO)
Lisa Poyneer (LLNL)
Ben Oppenheimer (AMNH)

ACWG Membership

- These represent Program, Study Office, SDT, and Community:

[Signatures when ready]

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AFTA Coronagraph Working Group



Workshop Organizers:

Gary Blackwood (NASA JPL)
Kevin Grady (NASA GSFC)
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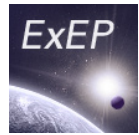
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Additional consultants participate at request of Steering Group



Consultants and Guests

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LIGHTSEY	WILLIAM
PANANYAN	OZHEN
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REUTHER	JAMES
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Executive Summary



- **Intended Results of this Briefing:**
 - Provide Recommendation for Primary and Backup coronagraph architectures for AFTA
 - Request APD approval and announcement
- **Executive Summary:**
 - Community working group conducted an open, technical evaluation using public evaluation criteria in a series of workshops and telecons since July 2013
 - We reached a broad consensus on the basis for the recommendation
 - Three strong technologies emerged, spanning the risk/performance continuum
 - The independent Technical Analysis Committee (TAC) concurred with the basis and with findings of ACWG
 - Recommendation:
 - **Primary Architecture:** Occulting Mask Coronagraph (OMC) that includes masks for Shaped Pupil Coronagraph (SPC) and Hybrid Lyot Coronagraph (HLC)
 - **Backup Architecture:** Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)
 - Recommendation best minimizes risk, preserves options to protect the project schedule, advances technologies, and preserves possibilities of increased science yield
 - Plan for Recommendation to reach TRL 5 is feasible (technically) and credible within existing resources (schedule, cost)

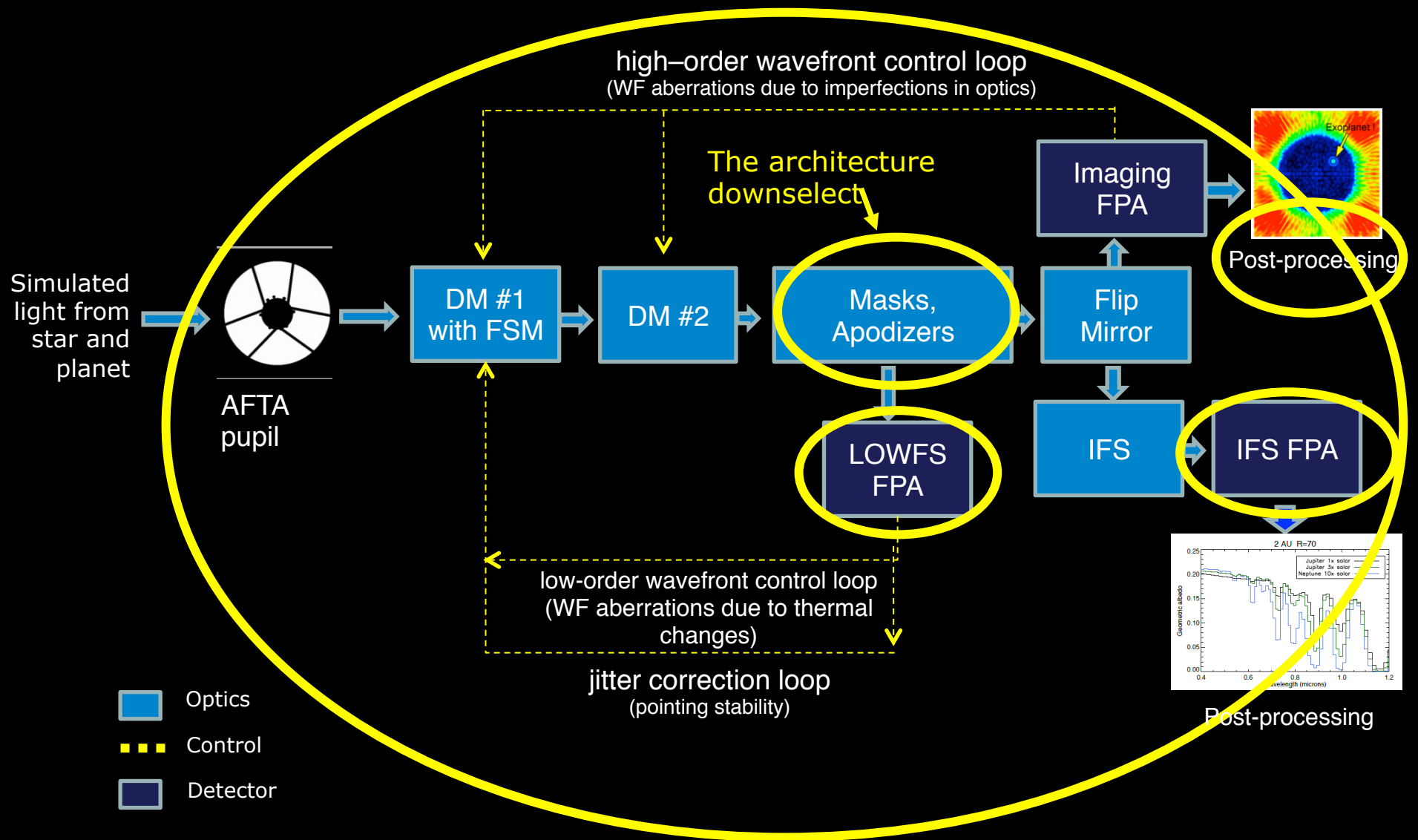
*See full package and decision memo at
<http://wfirst.gsfc.nasa.gov/>*

Coronagraph Instrument: Several Technologies

Example: Classical Lyot Coronagraph Design



ExoPlanet Exploration Program

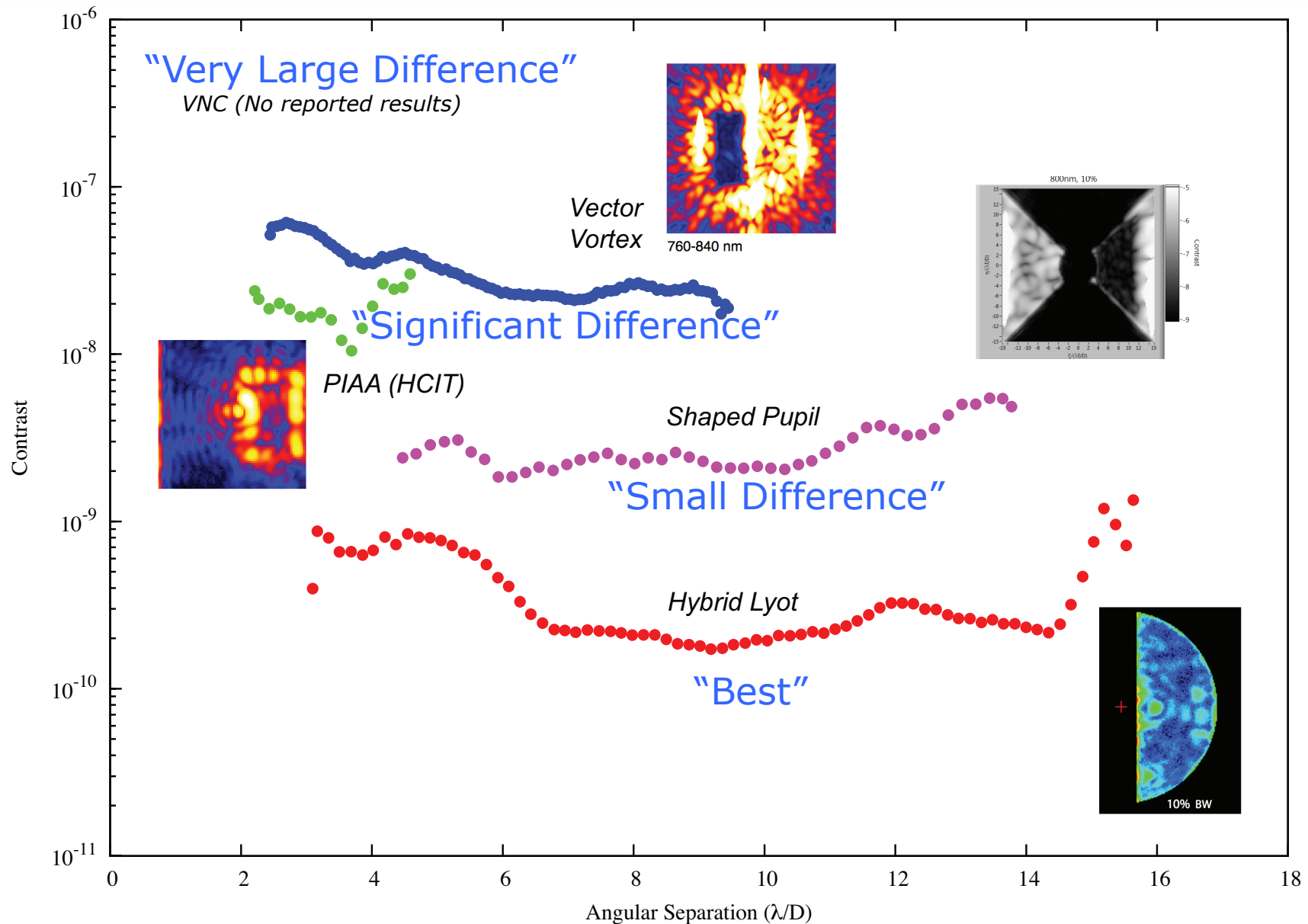


Visible Nuller – Phase Occulting (Clampin, NASA GSFC)

10% Bandwidth Results and Relative Assessment using an un-obscured pupil



ExoPlanet Exploration Program

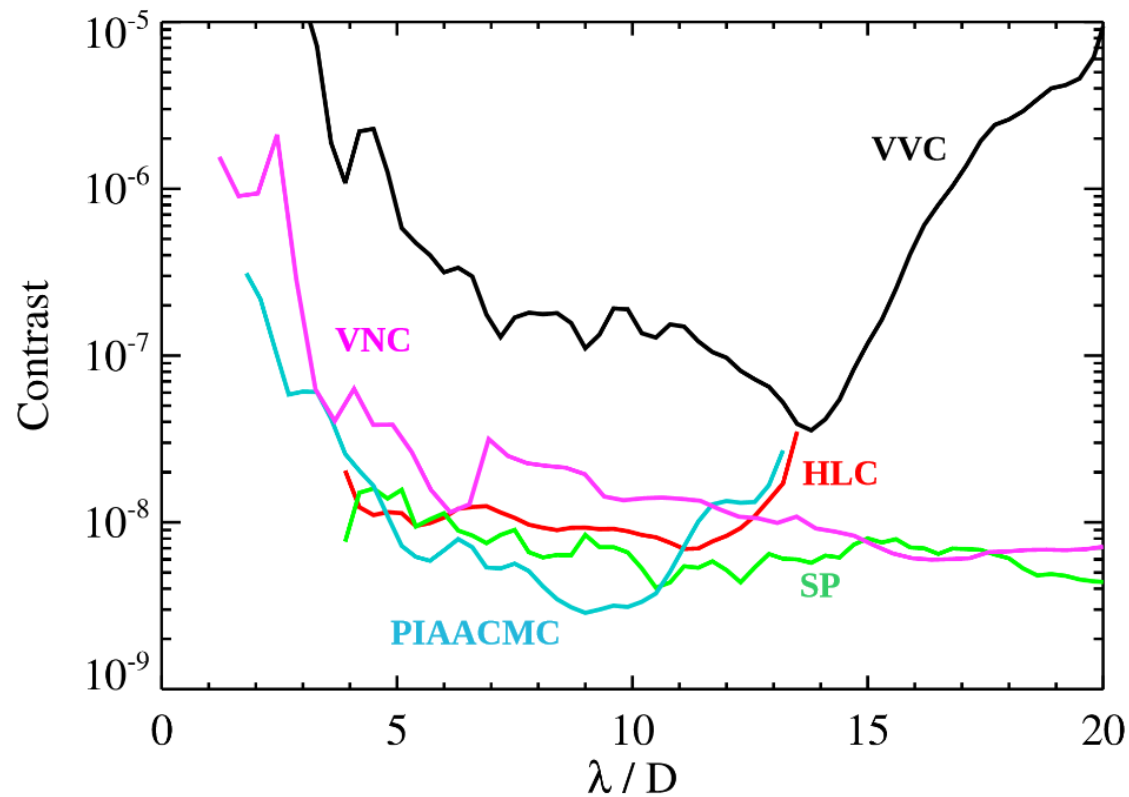


Intermediate Result: Contrast vs Angle from Star



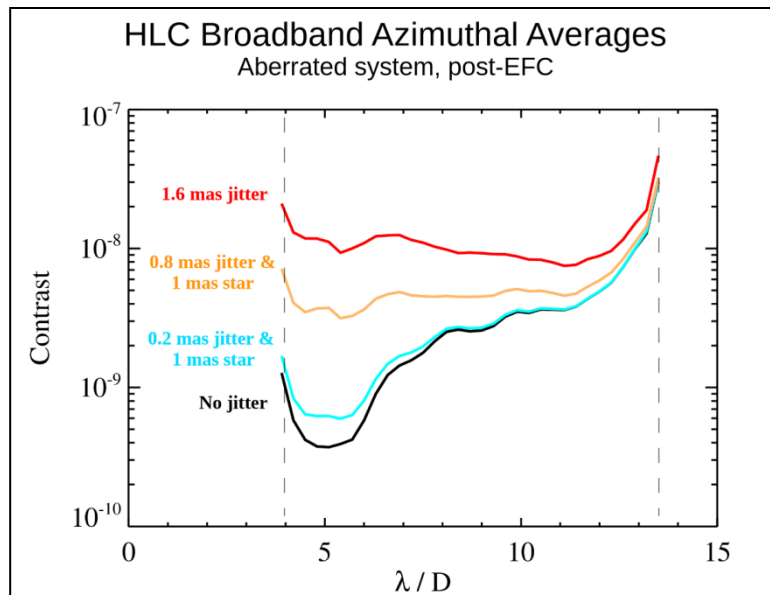
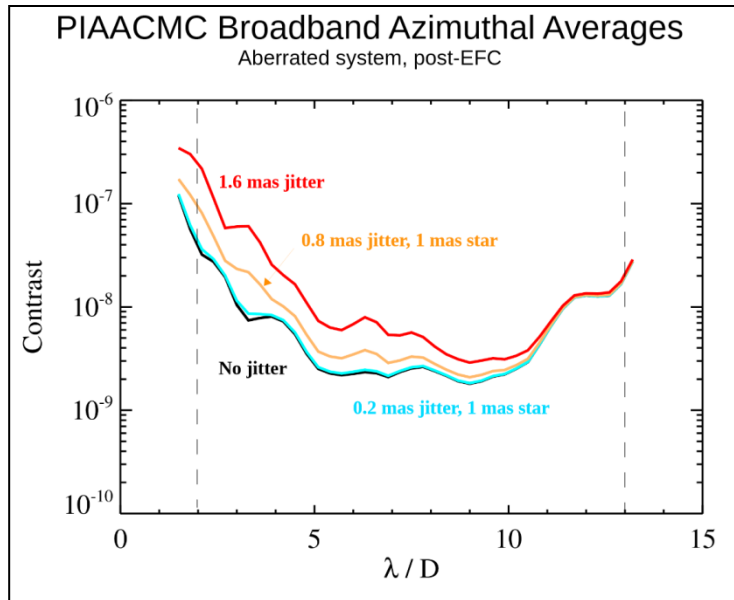
ExoPlanet Exploration Program

Modeling Results Summary 1.6 mas RMS jitter



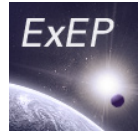
Each coronagraph's performance scales differently depending on jitter.

Intermediate Result: Performance Sensitivity to Jitter (examples)



- Dark Hole contrast improves with decreasing jitter
- Technologies have different sensitivities:
 - Strong sensitivity to jitter:
 - PIAACMC (shown)
 - HLC (shown)
 - VVC
 - VNC
 - Insensitive to jitter:
 - SPC (not shown)
- Results shown are for simple “opportunity” evaluation
- To fully realize yield of lower jitter, masks must undergo another design cycle at the lower jitter number

Science Results: Greater Science Yield for Lower Jitter, Greater Speckle Suppression



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Colors indicate pass/fail vs Threshold

Values indicate the Science Want "Beyond the Must" for Design Point (1.6mas, x10)

M1-T

Threshold	@1.6mas, x10	Value	SPC	PIAA	HLC	VVC	VNC2-DA
1	Wavelength: 430-980 nm, 10% bandpass, pol.		yes	yes	yes	yes	yes
2	Outer Disk: 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	6 (E-9)	5	6	5	50	10
3	Gas Giant Detection: Depth>10 for 4-14 RE 550 nm photometry of doppler planets	10	10	11	12	0	2
			1	3	0	0	0
Oppty	@ 0.2mas, x30	Value	SPC	PIAA	HLC	VVC	VNC2-DA
2	Outer Disk: 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	<6 (E-9)	2	0.4	0.6	100	0.3
5	HZ Disk: 10 zodi@1AU = 10e-9@ 130mas @450 nm	< 10 (E-9)	n/a	10	10	100	2
3	Gas Giant Detection: Depth>10 for 4-14 RE 550 nm photometry of doppler planets	>10	23	43	14	0	28
			8	31	15	0	30
4	Gas Giant Spectrum: Doppler planets at 550nm, 2 months	Max	1	12	5	0	19
6	Ice Giant Detection: Depth >2 for < 4RE	>2	0.4	3	3.6	0	6.1

- Calculations of exoplanet yields based on current catalogs of radial velocity exoplanets were adequate for comparing architectures.
- Yields are low due to conservative assumptions on spacecraft jitter and limitation of the current sample size
- We anticipate exceeding the SDT requirement of 6 exoplanet images with the AFTA coronagraph based on upcoming engineering studies and estimates of exoplanet population knowledge by 2023.

Colors indicate degree of Science Benefit for Oppty (0.2mas, x30)

Results: Full Trade Matrix

ExoPlanet Exploration Program

Decision Statement: Recommend one Primary and one Backup coronagraph architecture (option) to focus design and technology development

Description			Option 1		Option 2		Option 3		Option 4		Option 5		Option 6		Notes	
			SPC		PIAACMC		HLC		VVC		VNC - DA		VNC - PO			
<div>Musts</div>	Programmatic															
	M1 - T	Science: Meet Threshold requirements? (1.6, x10)	Yes	Yes	Yes	No	No	U								
	M2	Interfaces: Meets the DCIL**?	Yes	Yes	Yes	Yes	Yes	U	Yes	No	U					
	M3	TRL Gates: For baseline science is there a credible plan to meet TRL5 at start of FY17 and TRL6 at start of FY19 within available resources?	Yes	Yes	Yes	U	No	U								
	M4	Ready for 11/21 TAC briefing	Yes	Yes	Yes	Yes	Yes	No								
	M5	Architecture applicable to future earth-characterization missions	Yes	Yes	Yes	Yes	Yes	U								
<div>Wants</div>	Science		Weights		SPC		PIAACMC		HLC		VVC		VNC-DA		VNC - PO	
	W1	40														
	a	Relative Science yield (1.6, x10) beyond M1-T	Sm/Sig	Best	Sm/Sig	VL	VL									
	W2	30														
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability	Best	Best	Best	Best	Small									
	b	Relative sensitivities of post-processing to low order aberrations	Best	Sig	Sig	VL	U									
	c	Demonstrated Performance in 10% Light	Small	Sig	Best	Sig	VL									
	d	Relative complexity of design	Best	Small	Best	Small	Sig									
	e	Relative difficulty in alignment, calibration, ops	Best	Small	Best	Small	Sig/Sm									
	W3	30														
a	Relative Cost of plans to meet TRL gates	Best	Small	Best	Sig	Sig										
Wt. sum =>			100%													
Risks (all judged to be High consequence)			SPC		PIAACMC		HLC		VVC		VNC-DA		VNC - PO			
			C	L	C	L	C	L	C	L	C	L	C	L		
Risk 1	Technical risk in meeting TRL5 gate		L		M		M/L		M/H		H				PIAA trend over the last three working days lower, but recommendation to keep M	
Risk 2	Schedule or Cost risk in meeting TRL5 Gate		L		M		M/L		M/H		H					
Risk 3	Schedule or Cost risk in meeting TRL6 Gate															
Risk 4	Risk of not meeting at least threshold science		L		L		L		H		H					
Risk 5	Risk of mnfr tolerances not meeting BL science		L		L		L		M/L		H				One dissent, previous TDEM performance track record and Bala's assessment should be taken into account.	
Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt		L		M/H		M		M/H		M					
Risk 7	Risk that wrong architecture is chosen due to any assumption made for practicality/simplicity		open ended question, spawned evaluations on Risk 5, Risk 6, Risk 8, and Oppty 1													
Risk 8	Risk that ACWG simulations (by JK and BM) overestimate the science yield due to model fidelity		discussed; not enough understanding at this time to make an evaluation.													
Opportunities (Judged to be High benefit)			SPC		PIAACMC		HLC		VVC		VNC-DA		VNC - PO			
			B	L	B	L	B	L	B	L	B	L	B	L		
Oppty 1	Possibility of Science gain for 0.2marsec jitter, x30		L		M/H		M		L		H					

Final Decision, Accounting for Risks and Opportunities:

Indicates Sig. Discriminator in ACWG discussion

C = Consequence, L = Likelihood, B=Benefit

Indicates those few areas where consensus was not achieved

Indicates consensus achieved on balance of matrix

- Scores entered as group
- Consensus sought but not required; no dissent received
- Consensus reached after ~24 hours of group discussion on all points but those indicated in yellow
- Other colors for evaluation added afterwards for presentation clarity

TAC Assessment - Summary



ExoPlanet Exploration Program

• Report of the AFTA TAC:

AFTA TAC Report Conclusions:

- * All three occulting mask designs (SPC, HLC, PIAA-CMC) should continue to be studied and developed – not enough is known at present to choose a primary and a backup design.
- * Congratulations to the entire ACWG team for working together to perform this assessment on a tight schedule.
- * We need to maintain this productive, collegial approach as we move forward with AFTA.

AFTA TAC Report on ACWG#3 & ACWG#3.5 and Status of the ACWG Effort

The ACWG#3 workshop, held at JPL on November 20-22, 2013, featured presentations by the advocates for all six of the competing design concepts for an internal coronagraph instrument for the AFTA-WFIRST mission science payload. These presentations were followed by the reports of the instrument development team responsible for evaluating the relative attributes of each design concept with respect to key development and implementation factors. The primary evaluation factors were prescribed to be key programmatic considerations: estimated science performance, instrument interface compatibility, technology development timeliness and future mission applicability. Additional secondary evaluation factors addressed other science performance and technical engineering drivers. The workshop was characterized by a free and open debate between all the participants: the design advocates, the instrument development team, the ACWG Steering Group, the ACWG SDT, the AFTA TAC, the ACWG consultants, and the ExEP, ASO, and HQ managers, including those who participated virtually via Adobe Connect. The process was an exhausting one for some members of the instrument development team, who were only provided with their necessary inputs from other elements of the overall process during the meeting, rather than ahead of time, necessitating late night working and e-mail exchanges. The Science FOM evaluations suffered the most as a result. Nevertheless, the status of the Science FOM *relative* evaluations appeared to be mature enough to point toward a reasonably clear path forward for reaching a more definitive assessment of this key criterion.

At ACWG#3, all six of the competing design advocates were given equal opportunities to present and rebut their final designs for detailed analysis by the instrument development team prior to and during the workshop. Five of the six were able to do so, but even the sixth design (PO-VNC) was considered to the extent possible on the basis of existing information about its approximate design concept. Thus, the ACWG#3 workshop can be considered to have achieved its basic goal of allowing an open airing of an impartial assessment of all six competing design concepts for an internal AFTA coronagraph instrument. The ExEP and ASO managers are to be congratulated for having accomplished most of this key exercise, in spite of an extremely short schedule and the interruptions associated with the federal government shutdown for several weeks in the preceding month.

In order to complete the assessment process, ACWG#3.5 telecon was held on December 4, where the performances on the revised threshold, baseline, and opportunity science requirements were presented, as well as a final evaluation of the designs in the context of the master spreadsheet. The AFTA TAC's assessment of the spreadsheet is the primary focus of this report, but we also include a long list of more detailed points about the spreadsheet, its entries, and the overall process.

AFTA TAC Members

Alan P. Boss (chair), Carnegie Institution
Ben R. Oppenheimer, American Museum of Natural History
Joe Pitman, Exploration Science
Lisa Poyneer, Lawrence Livermore National Laboratory
Steve T. Ridgway, National Optical Astronomy Observatory

Results (Opportunity): Greater Science Yield for Lower Jitter, Greater Speckle Suppression



ExoPlanet Exploration Program

- Revisit Opportunity Science:

Colors indicate pass/fail vs Threshold

Values indicate the Science Want "Beyond the Must" for Design Point (1.6mas, x10)

M1-T

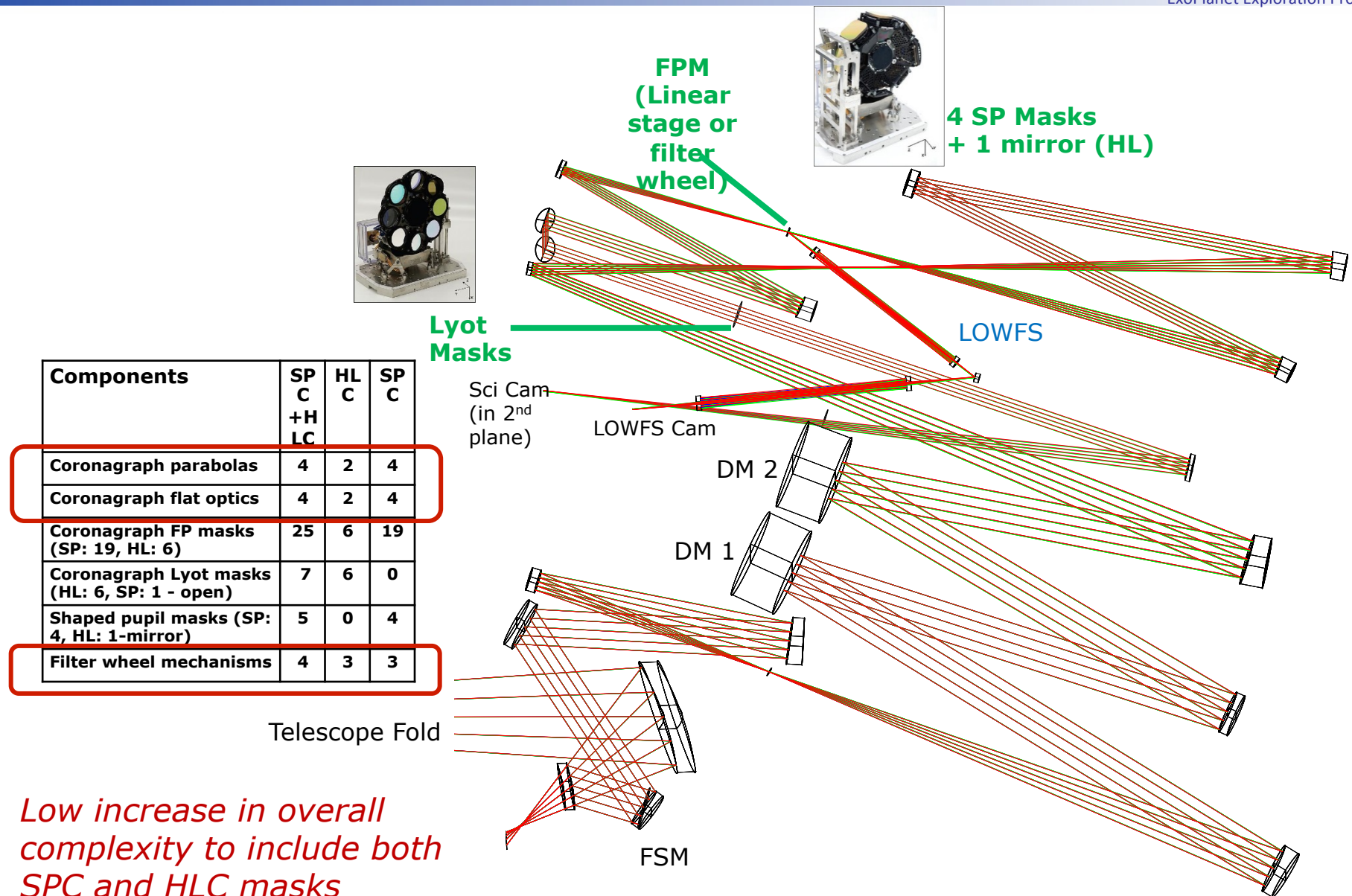
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3	Gas Giant Detection: Depth>10 for 4-14 RE 550 nm photometry of doppler planets	10	10	11	12
			1	3	0
Oppty	@ 0.2mas, x30	Value	SPC	PIAA	HLC
2	Outer Disk: 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	<6 (E-9)	2	0.4	0.6
5	HZ Disk: 10 zodi@1AU = 10e-9@ 130mas @450 nm	< 10 (E-9)	n/a	10	10
3	Gas Giant Detection: Depth>10 for 4-14 RE 550 nm photometry of doppler planets	>10	23	43	14
			8	31	15
4	Gas Giant Spectrum: Doppler planets at 550nm, 2 months	Max	1	12	5
6	Ice Giant Detection: Depth >2 for < 4RE	>2	0.4	3	3.6

3 leaders have different science strengths

Can we choose a primary architecture that plays to combined strengths?

Colors indicate degree of Science Benefit for Oppty (0.2mas, x30)

OMC: SPC + HLC Instrument Layout



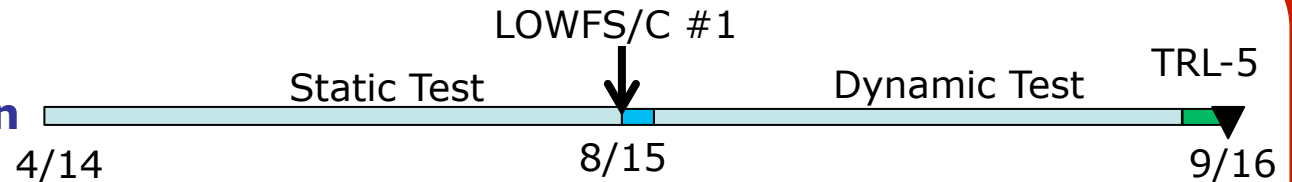
Technology Plan Overview (Preliminary)



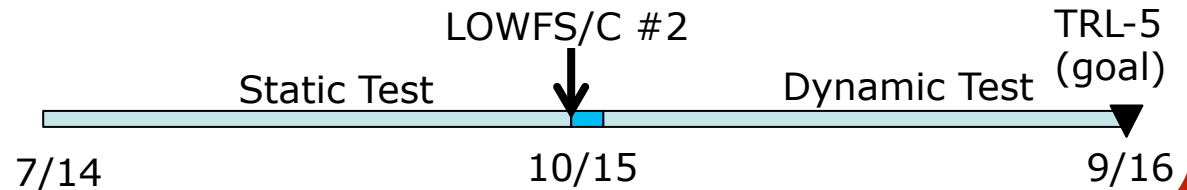
ExoPlanet Exploration Program

Planning Baseline:

HCIT1: Primary Design

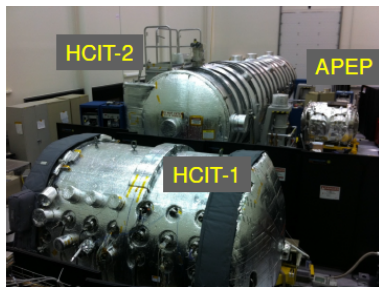


HCIT2: Backup Design

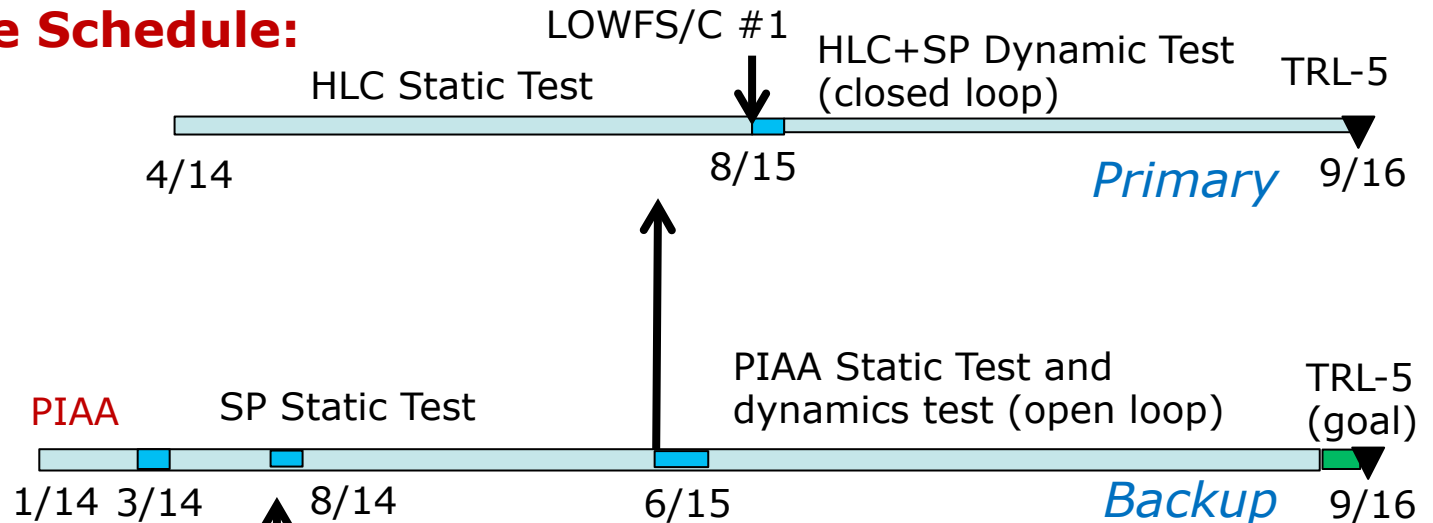


Option 7 Fits the Schedule:

HCIT1: HLC, SPC



HCIT2: SP, PIAA



PIAA TDEM refocused
on AFTA-relevant work

48x48 DMs

Backup does not include 2nd LOWFSC for closed
Loop dynamics. Could be added to reduce risk

Recommendation



- Summary Observation:
 - *Three leading technologies, all with different strengths and weaknesses, all will benefit from further design optimization cycles and high contrast lab testing.*
- Recommendation: Primary Architecture - **Occulting Mask Coronagraph (OMC)** and Back-up Architecture – **PIAACMC**
 - See full package, decision memo, and updated science estimates at <http://wfirst.gsfc.nasa.gov/>*
- Assumptions:
 - Plan is to mature both Primary and Backup architecture technologies. The OMC primary includes both HL and SP masks in a single optical design, and the current thinking is that we would fly both masks.
 - If programmatic, technical or scientific factors suggest off-ramping of one approach is appropriate (either part of the primary or the backup), the project will implement that, to maximize performance and minimize risk going forward.
 - HCIT testbeds will be utilized to exploit their maximum utilization based on the availability of hardware and the benefit to the project.
- Benefits:
 - OMC in its “SP mode” provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and “use-as-is” telescope. This translates to low cost/schedule risk and a design that has a high probability to pass thru the CATE process.
 - In its “HL mode”, the OMC affords the potential for greater science, however the increased risk is mitigated by the SP safety net.
 - PIAACMC offers the possibility of even greater science and at greater complexity. Hardware demonstrations and more detailed analyses are necessary to substantiate projected performance.
 - Taken together, the primary & backup architectures afford numerous “built-in descopes” and/or opportunities to accept greater risk due to the diversity of the approach.



Acknowledgements

- This was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration. © 2013. All rights reserved.
- Work also carried out by
 - NASA Goddard Space Flight Center
 - NASA Ames Research Center
 - Lawrence Livermore National Laboratory
 - Space Telescope Science Institute
- Work also carried out by Princeton University, University of Arizona under contracts with the National Aeronautics and Space Administration.



BACKUP

Final Trade Evaluation considering OMC=Option 7



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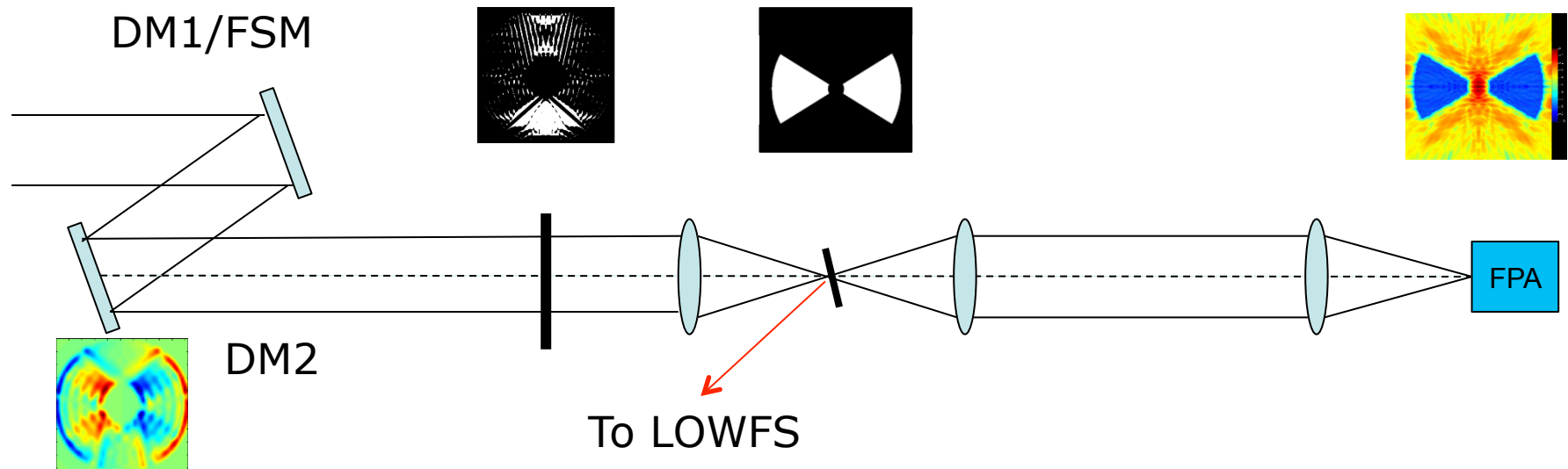
Decision Statement: Recommend one Primary and one Backup coronagraph architecture (option) to focus design									
Descr	Name			Option 7 OMC	Option 1 SPC	Option 2 PIAACMC	Option 3 HLC		
Evaluation	Musts	Programmatic		Yes	Yes	Yes	Yes		
	Wants		Weights	ABC	SPC	PIAACMC	HLC		
	W1	Science	40						
	a	Relative Science yield (1.6, x10) beyond M1-T		Sm/Sig	Sm/Sig	Best	Sm/Sig		
	W2	Technical	30						
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability		Wash	Best	Best	Best		
	b	Relative sensitivities of post-processing to low order aberrations		Best	Best	Sig	Sig		
	c	Demonstrated Performance in 10% Light		Best	Small	Sig	Best		
	d	Relative complexity of design		Best	Best	Small	Best		
	e	Relative difficulty in alignment, calibration, ops		Best	Best	Small	Best		
	W3	Programmatic	30						
	a	Relative Cost of plans to meet TRL gates		Small	Best	Small	Best		
Wt. sum =>			100%						
Risks (all judged to be High consequence)				ABC	SPC	PIAACMC	HLC		
				C	L	C	L	C	L
Risk 1	Technical risk in meeting TRL5 gate			L	L	M	M/L		
Risk 2	Schedule or Cost risk in meeting TRL5 Gate			L	L	M	M/L		
Risk 3	Schedule or Cost risk in meeting TRL6 Gate			L	L	L	L		
Risk 4	Risk of not meeting at least threshold science			L	L	L	L		
Risk 5	Risk of mnfr tolerances not meeting BL science			L	L	L	L		
Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt			L	L	MH	M		
Opportunities (judged to be High benefit)				ABC	SPC	PIAACMC	HLC		
				B	L	B	L	B	L
Oppty 1	Possibility of Science gain for 0.2marsec jitter, x30			M	L	MH	M		

Primary

Backup

- Define OMC = Occulting Mask Coronagraph
- Includes SPC+HL masks on different filter wheels
- OMC emerges as strongest candidate for Primary Architecture
- PIAACMC emerges as the candidate for the Backup Architecture

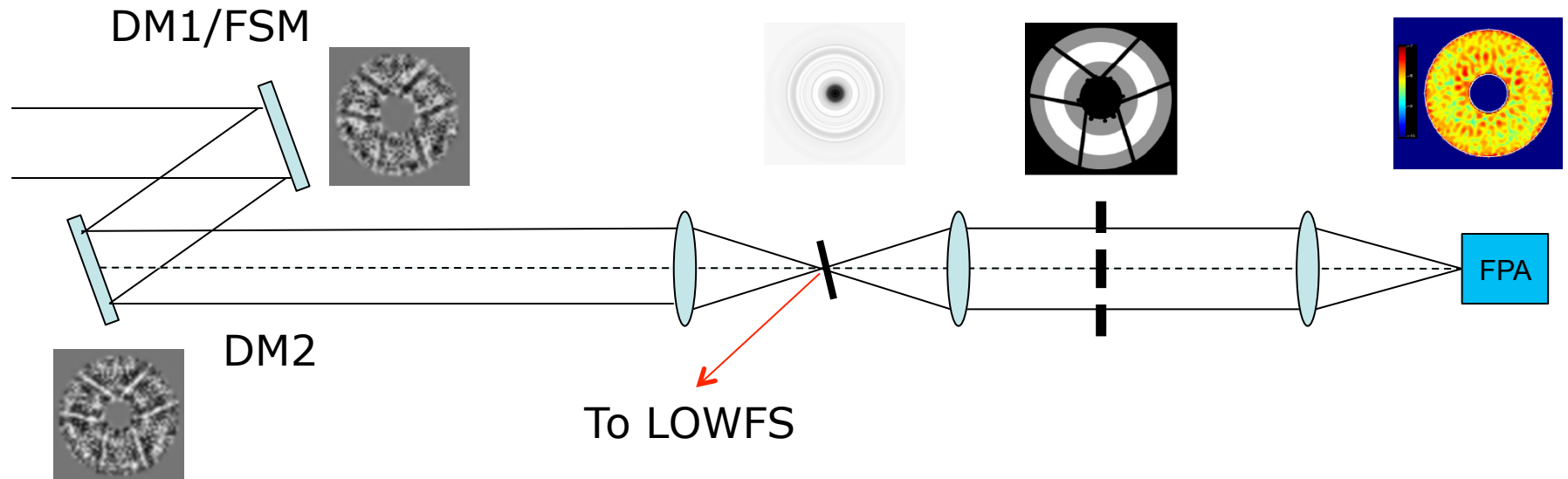
Shaped Pupil



DM1, DM2	Pupil mapping	Apodizer mask	Focal plane mask	Lyot stop	Inverse pupil mapping
Mild ACAD on both DMs		Binary reflection on filter wheels	Binary transmission, on filter wheel		

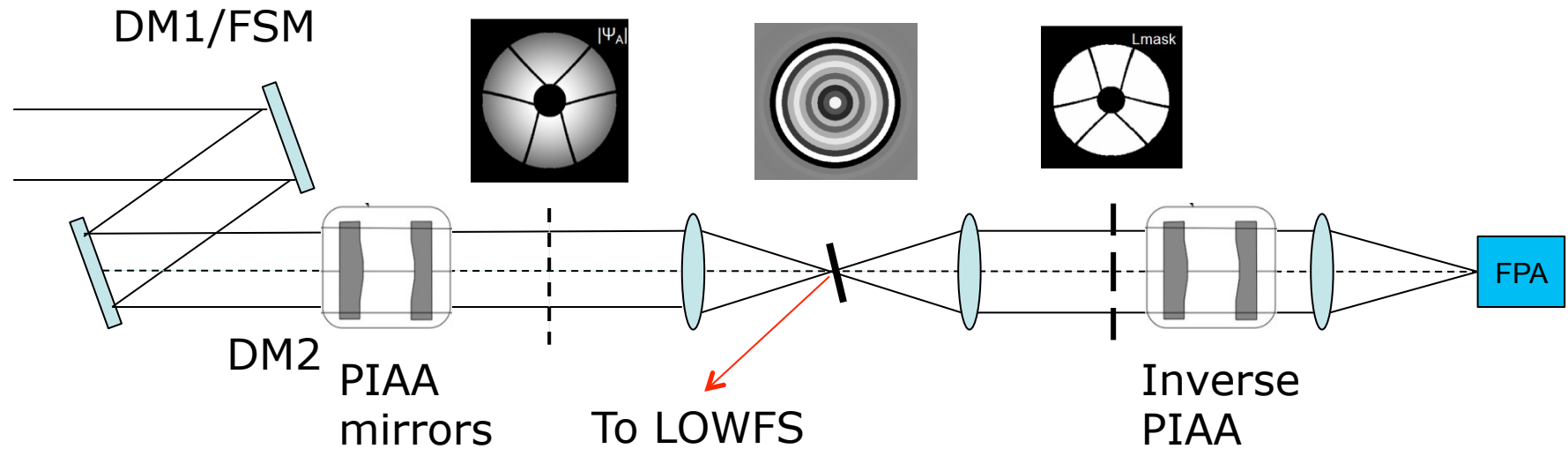
ACAD: Adaptive Correction of Aperture Discontinuities

Hybrid Lyot



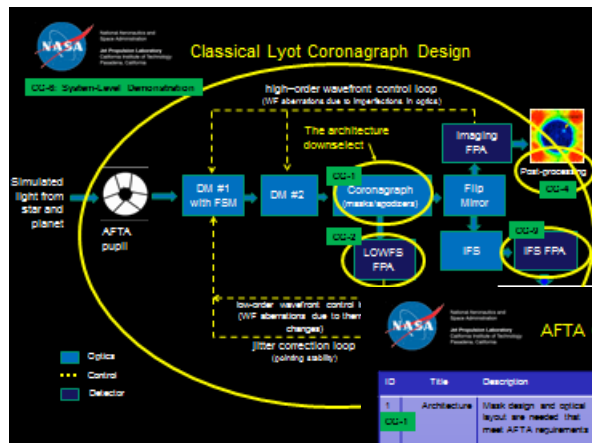
DM1, DM2	Pupil mapping	Apodizer mask	Occulting mask	Lyot stop	Inverse pupil mapping
Mild ACAD on both DMs			Complex transmission, on filter wheel	Transmission, grey, fixed	

PIAA - CMC



DM1, DM2	Pupil mapping	Apodizer mask	Occulting mask	Lyot stop	Inverse pupil mapping
Medium ACAD on both DMs	PIAA mirrors	Gray scale, filter wheels?	Phase transmission, on filter wheel	Transmission, binary, fixed?	Inverse PIAA mirrors

Prioritization: the Technology Gap List



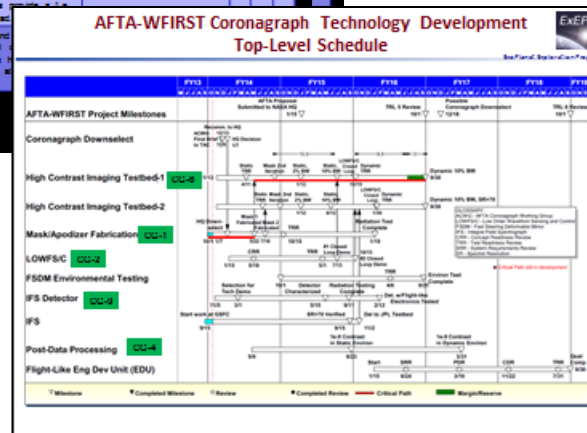
- Technology gaps identified █ and described, gaps technically quantified

AFTA Coronagraph Technical Gap List (1/2)

ID	Title	Description	Current	Required	I	U	T	ing
1	Architecture	Mask design and optical layout are needed that meet AFTA requirements	Two architectures have provided $\leq 10^4$ raw contrast with unobscured pupil	One or more architectures that meet requirements with AFTA pupil providing $\leq 10^4$ raw contrast	H	H	H	M
2	Low-order Wavefront Sensing & Control	Slowly varying large-scale optical aberrations may mimic the signature of an exoplanet	Tip/tilt errors have been sensed and corrected in vacuum at sub-MHz frequencies	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously	H	H	H	M
3	Breadboard demonstration	High-fidelity laboratory contrast demonstrations must include simulated science targets and light-like perturbations	Simulated star only (no planet) in vacuum with semi-static wavefront errors	Testing in a light-like environment with star, planet, and OTA simulator for the downstream of final architecture	H	H	H	M
5	Visible-IR Detectors	Low-noise detectors are needed to enable the characterization of exoplanet spectra	Si detectors cooled to 150 K provide the required dark current, 0.0005 e-/pixel/s	Dark current ≤ 0.0001 e-/pixel/s and read noise ≤ 0.1 e-/pixel in a GSD readout environment	H	H	H	M
4	Data Architecture post-processing	Software algorithms are needed to detect planets in data dominated by speckle noise	LOCO and principal component analysis H planets at 10^4					

- Prioritized for relative Importance, Urgency, and Trend

- AFTA TGL described to SMD/STMD



- Plans created to retire the top priorities in time